Investigation of Franz-Keldysh effect and carrier depletion effect in III-V/Si hybrid MOS optical modulator

◦Qiang Li[1], Chong Pei Ho[1], Shinichi Takagi[1], Mitsuru Takenaka[1] (1.Univ. Tokyo)
E-mail: liqiang@mosfet.t.u-tokyo.ac.jp

Introduction: Silicon (Si) optical modulator is a crucial component for optical communication system. Si metal-oxide-semiconductor (MOS) type optical modulators have demonstrated high modulation efficiency owning to the large change of refractive index induced by the accumulated free carriers at the MOS interface [1-3]. However, all the MOS type optical modulators work under the accumulation mode, which necessitate a large oxide capacitance, limiting the modulation bandwidth and energy consumption. In this study, we propose a III-V/Si hybrid MOS optical modulator based on Franz-Keldysh (FK) effect and carrier depletion effect. By combing these two effects together under negative bias, high modulation efficiency, large bandwidth and small energy per bit are achievable.

Device structure: Figure 1(a) shows the operation principal of the MOS type optical modulator. Carrier-accumulation MOS optical modulators operate under a forward bias (V_g>0 V). The density of accumulated charges can be modulated through a MOS capacitor. However, a large oxide capacitance (C_{ox}) limits the achievable modulation bandwidth and energy consumption. In contrast, when a reverse bias (V_g<0 V) is applied to a III-V/Si hybrid MOS capacitor, we have carrier depletion in both n-InGaAsP and p-Si layers. The carrier depletion in the heterogeneous MOS capacitor enables efficient, low-loss optical phase modulation. Simultaneously, a lower capacitance owing to the depletion capacitance is achieved, improving the modulation bandwidth. Moreover, in contrast to Si, the FK effect in III-V is also expected to contributes to the change in refractive index owing to the strong electrical field in the depletion layer. Figure 1(c) shows the electric field distribution with V_g = -0.6 V. Except for the edge, the electric field in the InGaAsP layer near the MOS interface is vertical with the intensity of around 100 kV/cm.

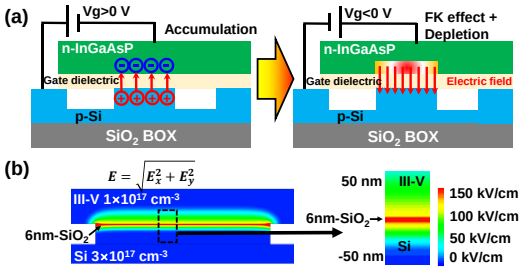

Fig. 1 (a) Schematics of III-V/Si hybrid MOS optical modulator working in different modes: accumulation or FK effect + depletion. (b) Electric field distribution under -0.6 V bias.

Result and Discussion: The phase shift as a function of gate voltage was measured and present in Fig. 2(a). By combing the FK effect and carrier depletion effect, the modulator exhibited a $V_\pi L$ of 0.11 Vcm. The theoretical calculation is also shown in Fig. 2(a). A good agreement between experimental data and theoretical calculation is observed. Fig. 2(b) shows the trade-off relationship between modulation bandwidth and energy per bit. As predicted, the combination of FK effect and carrier depletion effect can break the trade-off relationship, improving the modulation bandwidth and energy, simultaneously.

Acknowledgment: This work was partly commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

[1] A. Liu, J. Richard, L. Ling, S-R. D. Rubin, C. Oded, N. Remus, and P. Mario. Nature, vol. 427, no. 6975, pp. 615-618, Feb. 2004.
[2] J. Han, F. Boeuf, J. Fujikata, S. Takahashi, S. Takagi, and M. Takenaka, Nat. Photon., vol. 11, no. 8, pp. 486–490, Jul. 2017.
[3] J. H. Han, M. Takenaka and S. Takagi, *IEEE International Electron Devices Meeting (IEDM)*, 25.5, 2016.

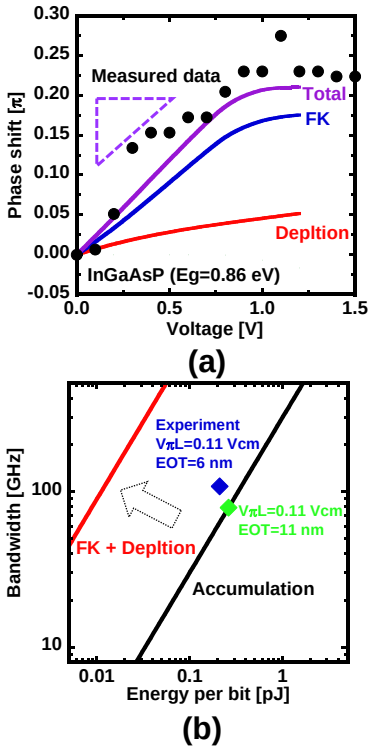

Fig. 2 (a) Measured optical phase shift as a function of gate voltage. (b) Trade-off relationship between modulation bandwidth and modulation energy.

© 2019年 応用物理学会